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# MULTISPECTRAL COATINGS

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**JANUARY 2010**
**Final Report**

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**14. ABSTRACT**
The objective of this project was to conduct research on multispectral coatings according to the following tasks: 1) Scratch Resistant Self-Assembled Coatings (SRSAC) incorporating nanomaterials to create thin hard coatings that can be placed over existing camouflage coatings and on appliqué films; 2) Highly Reflective Self-Assembled Coatings (HRSAC) utilizing dielectric stacks of materials tuned for high reflectance at 1064 nm; and 3) Broadband Infrared Self-Assembled Coatings (BISAC) yielding high reflectance over a broader portion of the infrared spectrum. The coatings research efforts included: 1) coating designs, 2) materials selection, 3) nanoparticle synthesis, 4) coating production, 5) optical property measurement, and 6) mechanical property measurement.

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# 1. Summary

Thin film metal oxide coatings have been used for electromagnetic filters from the UV to the infrared regions for over half a century. Conventionally, deposition of metal oxide layers onto a substrate has typically been accomplished using vapor deposition techniques[1] and more recently sol-gel methods[2]. These coatings provide very good optical and mechanical performance under abrasion, thermal cycles and variable humidity when applied to substrates with similar moduli and hardnesses. When conventional metal oxide coatings are applied to flexible, relatively soft substrates such as polymers, mismatches in mechanical properties can reduce adhesion or accelerate mechanical failures. This team developed anti-reflective optical filters utilizing self-assembled thin film polymer nanocomposites on polymer substrates. The team designed and manufactured a low-haze coating of fifteen discrete layers with a reflectance exceeding 90% near 1 μm wavelength.

# 2. Introduction

## 2.1 Project Scope

The project developed coatings for samples in the range of 8 cm in diameter. The technology was based on the self-assembly technology and nanomaterial fabrication/production techniques already used by Optical Dynamics Corporation (OCD) and its university researchers. Coatings containing nanoparticles in solvent/monomer mixtures were spun-cast, the solvent was evaporated, followed by photoinitiation or thermal initiation of the polymerization reactions. Optical Dynamics has commercialized several products based on this technology. The research team will use the polymerization systems generally known to it (poly(methyl methacrylate)) and metal oxide nanoparticles either available commercially or produced using literature or patent references. The coatings research efforts included: 1) coating designs, 2) materials selection, 3) nanoparticle synthesis, 3) nanoparticle dispersion preparation, 4) coating production, 5) optical property measurement, and 6) mechanical property measurement.

The University of Kentucky Research Foundation was the prime contractor, with subcontracts to Optical Dynamics Corporation for ultrathin film fabrication technology and the University of Louisville for surface analysis and fabrication of nanowires.

## 2.2 Project Objectives

This project used spin coating technology, new and commercial nanoparticle composites, and ODC's patented manufacturing systems to develop multispectral coatings systems for the Air Force. The specific military requirements were:

- <u>Task 1 – Scratch resistant self-assembled coating objective</u>. The research team modified ODC's existing low haze, hard coat nanocomposite technology to meet the Air Force's abrasion resistance, optical performance and flexibility requirements.

- <u>Task 2 – Highly reflective self-assembled coating objective</u>. The research team produced a highly reflective self-assembled coating by: 1) extending its current production capabilities for up to five layer stacks to higher number of layers while retaining control over the layer thicknesses and interlayer adhesions, and 2) using nanoparticle composites with greater differences in refractive index than those employed by ODC previously.

- <u>Task 3 – Broadband reflective self-assembled coating objective</u>. The research team produced a self-assembled coating with high reflectivity over a broader portion of the IR spectrum by: 1) continuing the extension of multilayer technology to high numbers of layer than accomplished for Task 2.1, 2) continuing the development of nanocomposites with greater differences in refractive index, and 3) exploring the use of nanoparticle mixtures, including different compositions and aspect ratios, such as nanowires.

## 2.3 Timeline

The project had its kick-off meeting on 28 November, 2005 and ended 30 September, 2008.

# 3. Methods, Assumptions, and Procedures

Details on the methods, assumptions and procedures used to accomplish the various research tasks are included in the papers published in full or in part sponsorship of this work.

# 4. Results and Discussion

## *4.1 Nanocomposites for Self-Assembled Coatings*

The design and production of optical filters is mainly accomplished through the combination of thin films with unique refractive indices [3]. These are typically dielectric and metal films that are almost exclusively deposited using vacuum deposition. Although these materials have been studied extensively, they have significant disadvantages with respect to the complex processing steps[4] and limited mechanical flexibility,[5] which can be particularly important when they are applied over soft materials, such as polymers or polymer coatings. Nanocomposites composed of inorganic nanoparticles embedded in an organic polymer matrix directly address these issues. The challenges for nanocomposites are to alter the optical properties of a material without affecting the visible transparency of the final article.[6] The need and methods to build nanocomposites of randomly dispersed nanoparticles for high visible transparency is the focus of this project.

The spin coating method to deposit polymers has been widely studied and allows for simple, low cost depositions of thin films. Thicker films, i.e. on the order of several microns, present a greater degree of light scattering, often hampering their use in optical applications especially when the mismatch in refractive index is large. It is therefore necessary to find a way to deposit nanocomposite films with low light scattering that still maintain the desired refractive index and mechanical strength.

The state of the art of the deposition of thin film optical filters includes traditional techniques such as vapor deposition and sol-gel coatings. These coatings are poorly matched to polymer substrate in the strain domains and will typically exhibit brittle failure under flexural loading caused by moderate mechanical and/or thermal stresses.

### 4.1.1 Hybrid Inorganic-Organic Materials

In the past few decades there has been a lot of excitement about hybrid inorganic-organic materials that would have a broad range of refractive indices.[2] The advantages of these materials are the low processing costs and extended range of strain over ceramic films. Most research has been in sol-gel synthesis techniques in which the gel networks are not completely sintered resulting in a hybrid inorganic-organic composite.

For the sol-gel process to work on polymer substrates, the processing temperatures had to be reduced. Many researchers cite examples of modified sol-gel films that could be cured at moderate temperatures[7], including filters in the NIR. The films relied on a process that created an incomplete condensation of the sol-gel creating an inorganic-organic hybrid, and were named Nanomers by Schmidt[8]. The group at the Institut fuer Neue Materilien GmbH in Germany have developed several applications (thin films and thick lenses). Recently some researchers have shown that the films can be also cured using UV radiation. These films tend not to have the mechanical performance of inorganic films.[9]

### 4.1.2 Inorganic-Organic Nanocomposites

Nanocomposites composed of inorganic nanoparticles in a polymer matrix offer a unique platform to engineers; the optical and mechanical properties of the composites can be changed by changing the nanoparticles and their loading levels.[10, 11, 12] The strain domains of these films are very similar to those of the polymer substrate and as such do not exhibit the crazing or cracking often associated with films applied through vapor deposition.[13] Unlike the sol-gel synthesis techniques described before, the inorganic particles exist in the crystalline phase, with controlled refractive indices and mechanical properties.

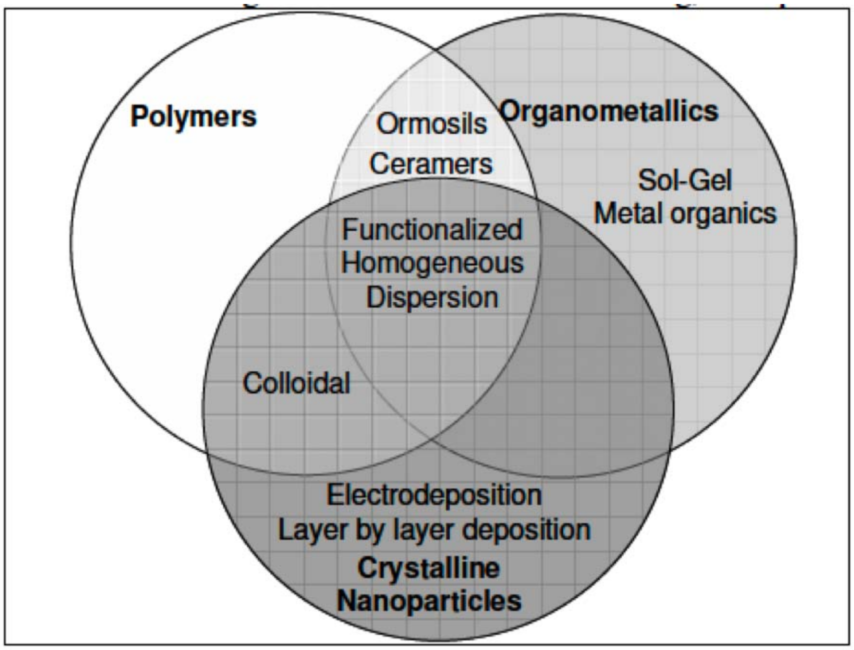


Figure 1. Nanocomposite Films via Three Basic Building Blocks: crystalline nanoparticles, polymers and organometallics

As there is no need to use high heats to establish the coating, the processing of these plastics is straightforward. Inorganic-organic nanocomposites can be assembled from three distinct components: crystalline nanoparticles, polymers and organometallics as shown in the Venn diagram (see Figure 1). Organometallics are the precursor chemistries for the sol-gel process and can be used to produce thin film filters. Adding a monomer to a colloidal sol and curing results in a nanocomposite such as an Ormosil; however, the nanoparticles are amorphous. An inorganic-organic nanocomposite can be synthesized by incorporating a colloidal dispersion of nanoparticles into a monomer and curing. Colloidal dispersions of crystalline nanoparticles are available and often utilize electric double layers to maintain the particles in stable dispersions. If the nanoparticles do not actively participate in the curing, these discrete particles can act as defects, reducing the mechanical strength of the solid. The size of the nanoparticles must be controlled to prevent haze and light scattering. Metal oxides are preferred as they will be relatively inert in typical exposure enviroments, particularly those with refractive indices higher or lower than the polymer phase.

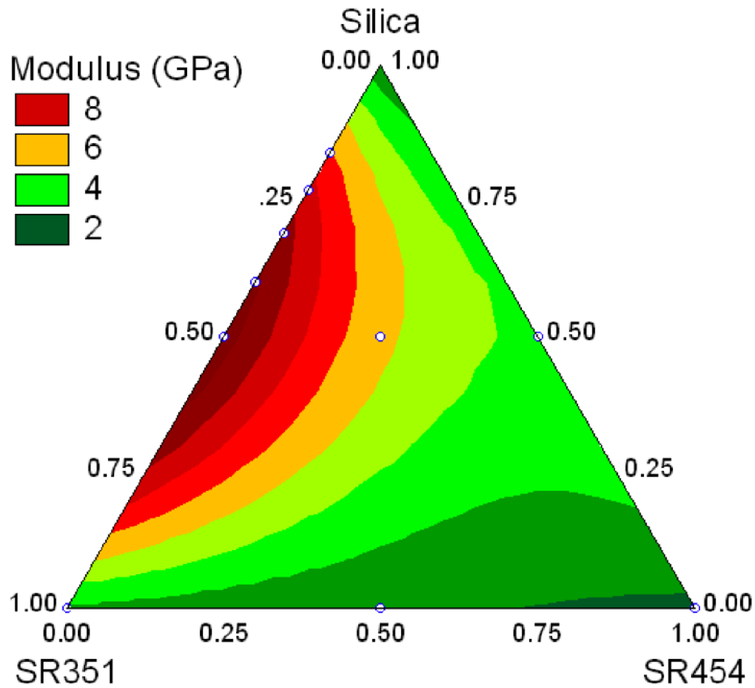

Figure 2. Ternary Diagram of Nanocomposite Moduli

The mechanical properties of nanoparticle/polymer nanocomposites can be controlled in a number of ways. Nanoparticle loading generally increases the elastic modulus, but decreases the elongation at break. The modulus can also be changed by using mixtures of monomers for the polymer, as shown in Figure 2. The two monomers used for this series of nanocomposites were Sartomer SR 351 and SR454. Data points are shown as open circles; moduli regions are estimated by software. SR-351, trimethylolpropane triacrylate (TMPTA), is a low viscosity, low volatility liquid monomer for free-radical polymerizations. SR-454, 3 mole ethoxylated trimethylolpropane triacrylate, is a low skin irritation, fast curing monomer for use in free radical polymerization. The ethoxylated acrylate has a more flexible chain and a lower modulus. It is possible to vary the modulus significantly merely by changing the weight ratio of the two monomers and the solids loading. Note that solid loadings greater than ~73% are usually not possible to achieve, based on the close packing for spherical particles, i.e., materials with > 75% silica are not usually practical.

### 4.1.3 Dispersion Stability

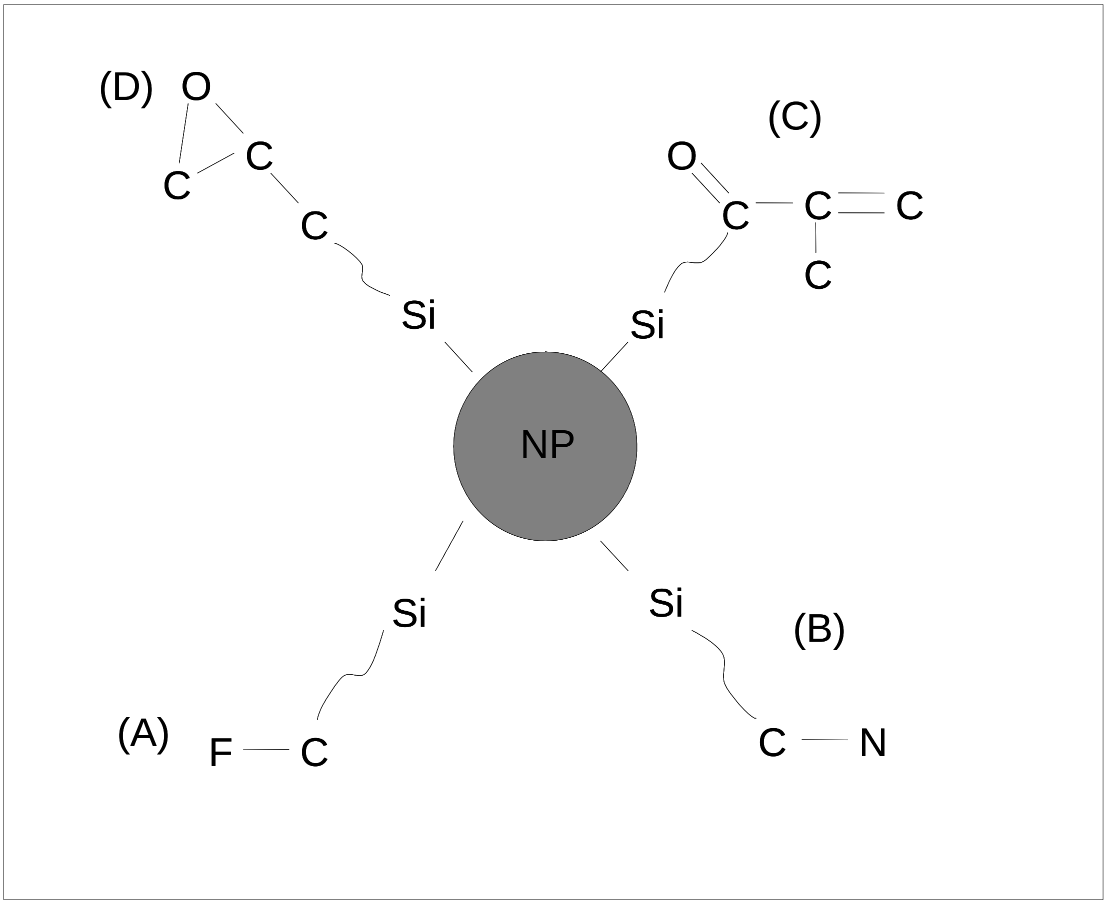


Figure 3. Nanoparticle with Organosilanes Attached.

Nanoparticle dispersions usually need to be stabilized by electrostatic or steric mechanisms. Surfactants would alter the overall refractive index of the material. Electrostatic stabilization might have a similar effect. Steric stabilization of the nanoparticles using coupling agents (some examples are shown in Figure 3) can be used to match the surface energy of the nanoparticles to the media. By functionalizing the crystalline nanoparticles with a polymerizable group, chemical bonds between the nanoparticles and the polymer matrix are formed. This creates a route to produce a homogeneous dispersion of nanoparticles in a polymer matrix, which is the key to producing nanocomposites that have high visible transparence while maintaining the elastic properties of the polymer. There has also been some interest in the use of nanostructured materials such as tubes and wires that would improve the mechanical performance of films. Carbon nanotubes embedded into a polymer substrate at a low volume percentage improve the modulus of the nanocomposite, but since they have lengths on the scale of microns, they do not form transparent films. The functionalization of the nanoparticles is extremely important for dispersing nanoparticles randomly throughout a polymer matrix. Dispersion of nanoparticles in a liquid and a solid can be aided by functionalization of the surface.[14] There are several functionalization schemes that exist in the literature including the use of ions[15], surfactants, ligands[16], polymers[17], coupling agents[18] and shells such as silica[19] or polymers.[20]

Figure 2 shows four different organosilanes. Coupling agents can be used to change the surface properties of the nanoparticles. For example:

- If the coupling agent contains fluorine (A), the nanoparticle surface could be hydrophobic or lipophilic.
- If the coupling agent contains a cyano group (B), it will be positively charged in aqueous environments.
- If the organosilane contains a polymerizable group, the nanoparticle can be chemically attached to the polymer matrix, improving mechanical properties. Possibilities include C=C double bonds for free radical polymerization (C) and an oxirane group for epoxide reactions.

## *4.2 Mechanical Performance of Nanocomposites*

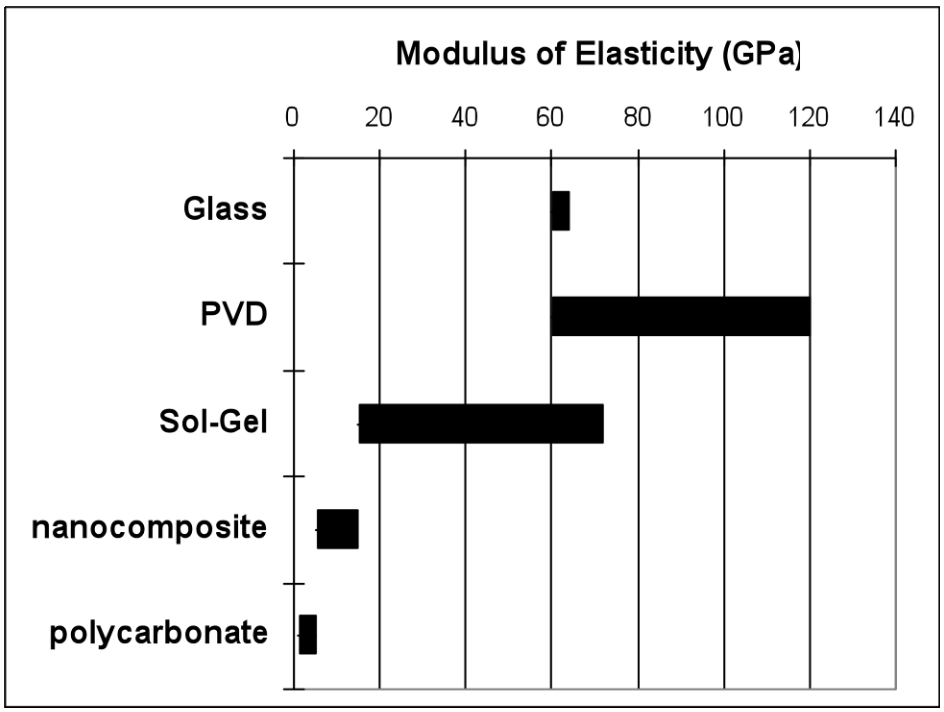


Figure 4. Moduli of Elasticity of Substrate and Ultrathin Layer Materials.

### 4.2.1 Moduli of Elasticity Ranges for Typical Substrates and Coatings

As shown in Figure 4, PVD and sol-gel ceramic coatings have moduli similar to that of glass, but higher than polymer substrates such as polycarbonate. Polymer nanocomposite moduli are closer those of soft substrates.

### 4.2.2 Polymer Nanocomposites for Ophthalmic Lens Applications

Nanocomposite thin films reported here consist of metal-oxide nanoparticles and a UV-cured acrylate matrix. The nanoparticles are selected to engineer the refractive index of the individual layers; they also improve the mechanical properties of the layers. The spinning dope consists of nanoparticles dispersed in a solvent with monomer and photoinitiator. Layers of alternating refractive index are spin coated and polymerized, forming a stack with specific optical properties (reflective, anti-reflective or chromophoric). Good transparency and low haze coatings require that the nanoparticles are not agglomerated or aggregated, and that the primary particle size be much less than the layer thickness (~100 nm).

### 4.2.3 Manufacturing Optical Filter Coatings

Figure 5. ODC Lens Manufacturing System

The individual layers in the stack were spin-coated onto a substrate using a lens manufacturing system by Optical Dynamics Corporation (shown in Figure 5). Spin coating controls the layer thickness by balancing the centrifugal forces of a developing thin film to the viscous forces that increase as evaporation takes place. The repeatability of this method is excellent as long as the coating environment is controlled to maintain a constant evaporation rate [21]. A surface with roughness on the order of several microns can also be coated. After the solvent is evaporated, a 50-150 nm film of a UV-curable monomer and nanoparticles remain. The film is then cured using a pulse xenon UV source lamp, leaving a polymer nanoparticle composite. Subsequent layers are then added on top of the previous layer to build the filter. A lens with a simple two layer ophthalmic filter over a protective nanocomposite hardcoat is shown to the right. The nanocomposite refractive index and modulus are optimal for solid loadings in the range of 60-70 vol%.

### 4.2.4 Mechanical Properties of Nanocomposite Coatings

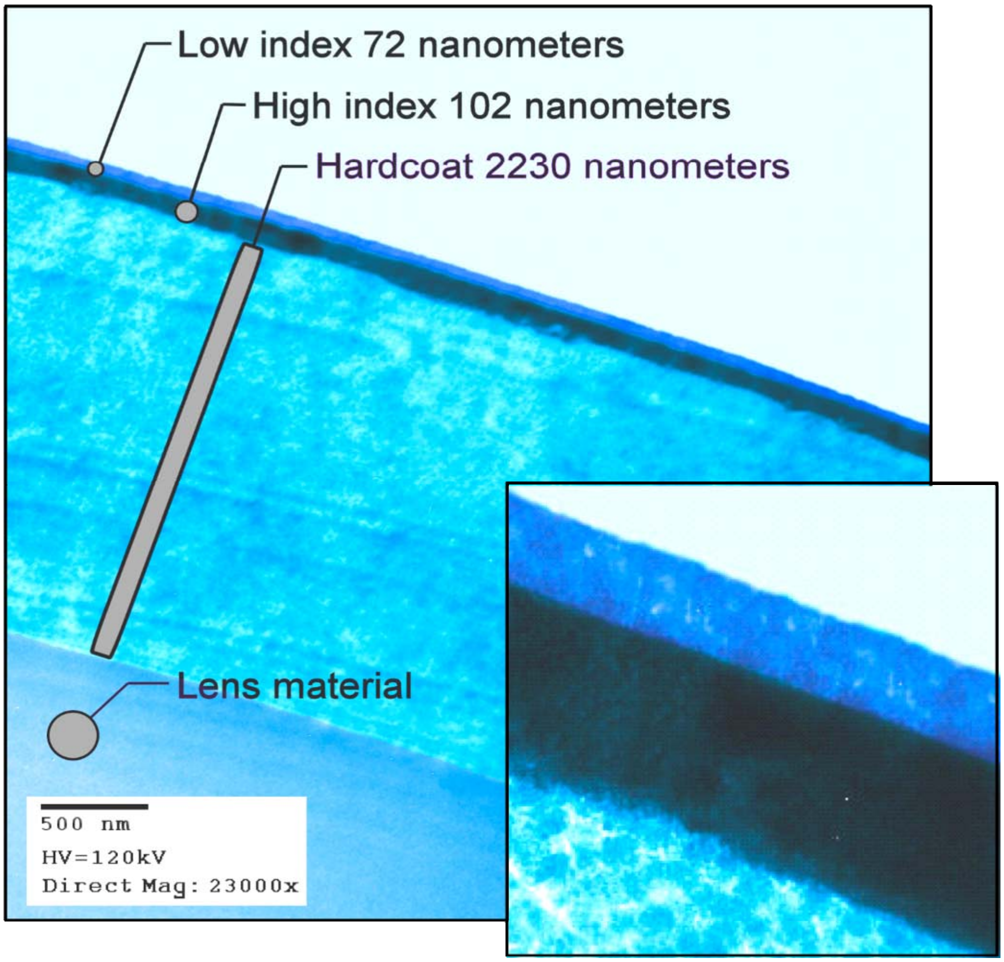


Figure 6. Cross-sectional Image of Multilayer Stack on Lens Substrate

Figure 6 shows a stack of multiple ultrathin composite layers on a lens substrate. The lens material is shown in the lower left corner. The 2230 nm hardcoat (silica nanoparticles in a cross-linked methyl methacrylate matrix) provides protection from scratching of the lens material. The low index/high index stack that supplies an antireflective property covers the hard coat. The multilayer stack is actually manufactured in reverse order, starting with the deposition of the low index material on the mold, then the high index material, and then the hardcoat material. The mold is then backfilled with lens material for the final polymerization.

The team has a body of work investigating the use of nanoparticles in a UV-curable monomer system. The stabilization methods of nanoparticles favored the use of monomers that were compatible with the solvents. The monomers chosen were UV-curable acrylates.[12] These systems have been shown to be more flexible than the traditional vacuum deposition coatings which when deposited onto a polymer will fare much better to point loads. A demonstration of this is shown in Figure 3 which is a comparison of the mechanical response of the coating to a point load using nanoindentation techniques [22]. The results show that the nanocomposite does not exhibit the brittle failures and should therefore perform better in systems where high visible transparence is important.

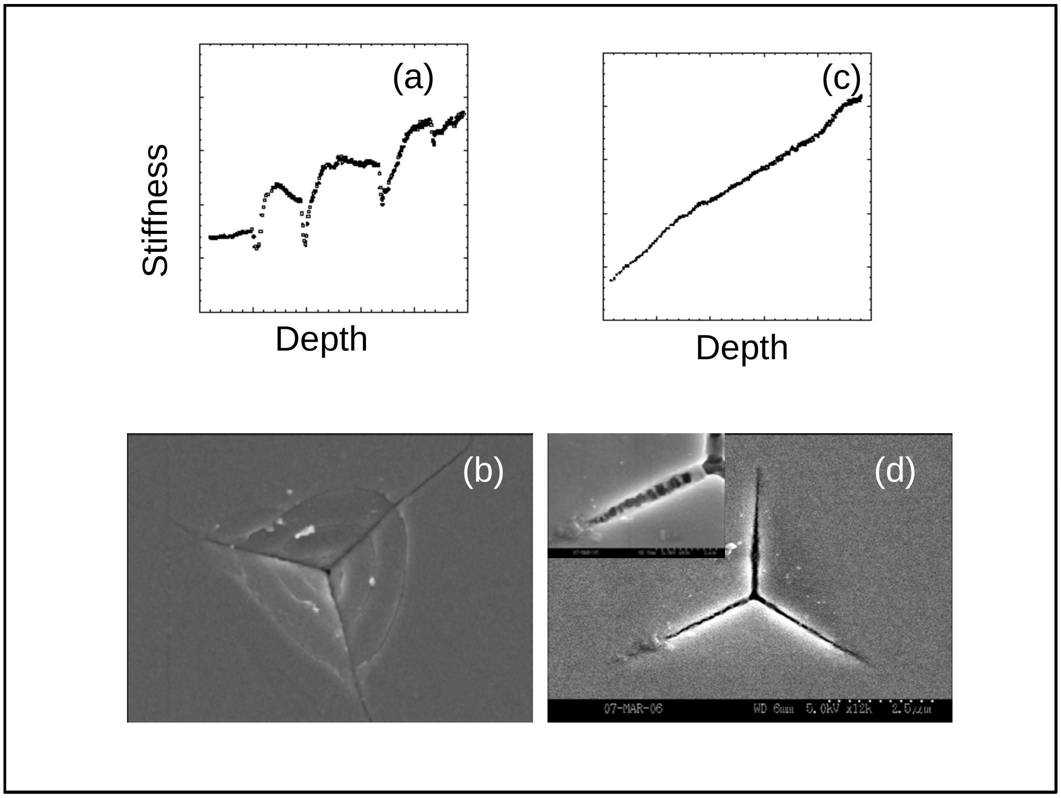


Figure 7. Nanoindentation Point Loading of PVD and Nanocomposite Coatings.
A traditional vacuum deposition thin film [(a), (b)] and a nanocomposite coating [(c), (d)] on plastic substrate.

Point loading of a vacuum deposition film and a nanocomposite coating are shown in Figure 7. The stiffness measurement (Fig. 7a) of the ceramic coating shows discontinuities as the indentation depth increases; these are linked to the times when the brittle coating cracks. The SEM image of this coating film showed the brittle fractures (Fig 7b). The stiffness response of the nanocomposite (Fig. 7c) showed no discontinuities, indicating that the failure is ductile. The SEM image (Fig. 7d) of the nanocomposite indentation showed that there are no fractures, and that the film was cut by the indentation tip. The ceramic coating was deposited using PVD and the total thickness of the stack was 330nm. The nanocomposite was deposited as described here and had a thickness of 300 nm.

Very thin layers of ceramics can be deposited onto a transparent, polymer substrate to control surface reflectance. However, nanocomposite films better match the mechanical performance polymer substrates, and can be made at much lower costs. This deposition technique operates at atmospheric conditions using dispersions that are readily available and stable for several months. The deposition of the films must result in discrete layers in which the nanoparticles are dispersed homogeneously. This will aid in the optical clarity of the films and should allow these films to undergo strains that may be typical of polymers.

### 4.2.5 IR Mirror

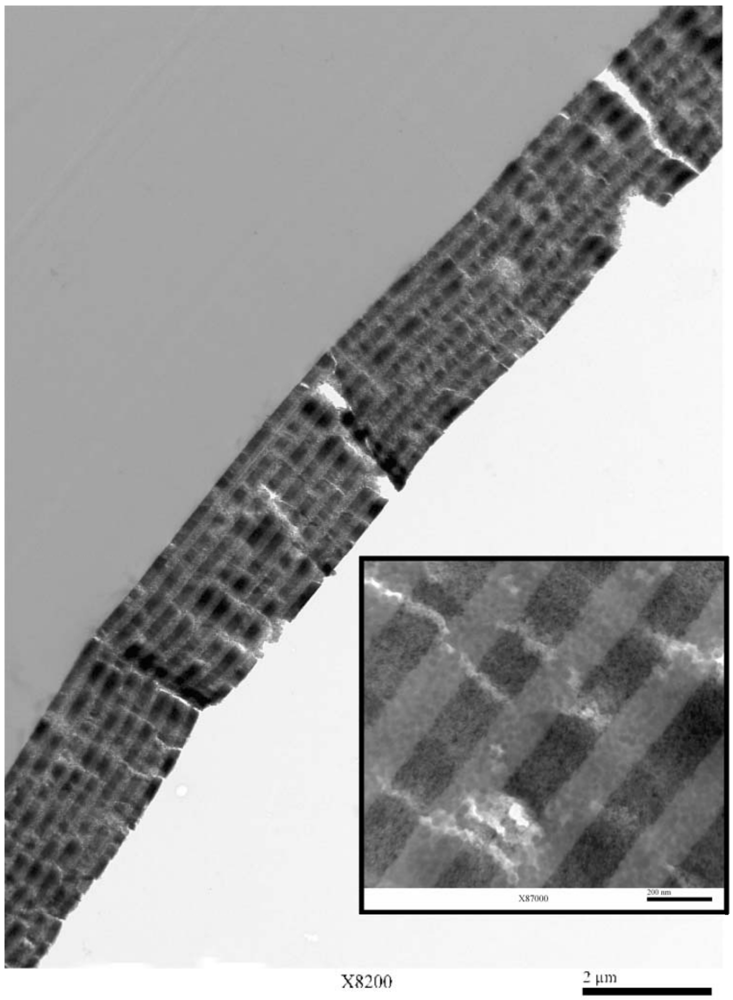


Figure 8. 15 Layer Stack with 90% Reflectance in the IR.

Excellent control over the spin coating process and material properties permits complex optical filters to be designed and manufactured, such as the antireflective coating, or IR mirror shown in Figure 8. A ¼ wavelength stack was designed for a reflectance > 90% at a wavelength of 1060 nm. The low index layer had a thickness of 180 nm and $n_d$=1.48 and the high index layer had a thickness of 140 nm and $n_d$ = 1.88. Layer thicknesses were confirmed using a profilometer. The figure to the left shows a microtomed cross-section of the fifteen-layer stack on polycarbonate. The polymer nanocomposite layers have higher moduli than the polycarbonate, and fracture during microtoming, while the homopolymer (light gray) fails ductilely.  The fracture cracks extend through the layer interfaces rather than run along them, demonstrating excellent interlayer adhesion.

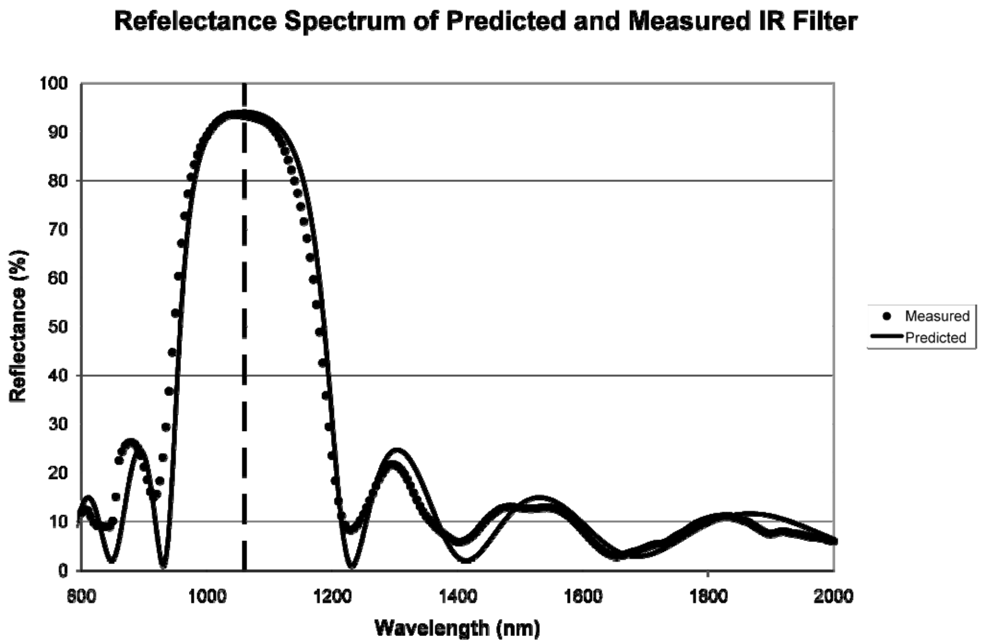


Figure 9. Comparison of Stack Design with Measured Performance.

The UV-Vis spectrum from 800 to 2000 nm wavelengths is compared to the theoretical response as computed using TFCalc. The data show a very good correlation between the measured and calculated responses of the filter (Fig. 9).

## *4.3 Project Outcomes*

### 4.3.1 Students

Two students have received training associate with this award. Kebin (Eddie) Geng was supported for some of his Ph.D. research at the University of Kentucky on this award. He defended his dissertation, Mechanical evaluation of nanocomposite coatings, in 2006. The dissertation is posted: http://lib.uky.edu/ETD/ukymsen2006d00476/Dissertation.pdf. His work focused on the mechanical properties of ultrathin film nanocomposite coatings. He has been a research engineer for PolyOne Corporation (Avon Lake, OH) since graduation, working on their nanocomposite product line. In 2009, he obtained a green card. He has two patents based on his work with PolyOne.

G. Chris Laine, a Ph.D. candidate in Chemical Engineering at the University of Kentucky, has received modest training associated with this award. He spent several weeks in the lab of Rachel Jacubiak, investigating whether some of the advanced instrumentation of the Materials and Manufacturing Directorate would be helpful in analyzing the morphology of our nanocomposites. He has continued working in the area of nanocomposites, and is now evaluating a rapid screening technique to identify potential effects of engineered nanomaterials (ENMs) on biomimetic membranes.

**4.3.2 Publications/Presentations**

Task 1. Scratch-resistant self-assembled coating objective.
The team published a paper on the scratch-resistant mechanisms for ultrathin film nanocomposites.

Druffel, T.; Geng, K.; Grulke, E., Mechanical comparison of a polymer nanocomposite to a ceramic thin-film anti-reflective filter. *Nanotechnology* **2006,** *17* (14), 3584-3590.

Abstract. Thin-film filters on optical components have been in use for decades and, for those industries utilizing a polymer substrate, the mismatch in mechanical behaviour has caused problems. Surface damage including scratches and cracks induces haze on the optical filter, reducing the transmission of the optical article. An in-mold anti-reflective (AR) filter incorporating 1/4-wavelength thin films based on a polymer nanocomposite is outlined here and compared with a traditional vacuum deposition AR coating. Nanoindentation and nanoscratch techniques are used to evaluate the mechanical properties of the thin films. Scanning electron microscopy (SEM) images of the resulting indentations and scratches are then compared to the force deflection curves to further explain the phenomena. The traditional coatings fractured by brittle mechanisms during testing, increasing the area of failure, whereas the polymer nanocomposite gave ductile failure with less surface damage.

Task 2. Highly reflective self-assembled coatings.
The team published two papers on nanoindentation to measure the nanocomposite mechanical properties in situ (these are ‘hard coat’ materials over the ‘soft’ substrate material) [23, 24], plus one on the effects of nanoparticles in these nanocomposites. [25]

Geng, K.; Yang, F.; Druffel, T.; Grulke, E. A., Nanoindentation-induced delamination of submicron polymeric coatings. *Polymer* **2007,** *48* (3), 841-848.

Abstract. An elastic model is developed to est. the interfacial strength between a submicron surface coating and a compliant substrate. The anal. uses a shear-lag model and assumes the plane-stress state in the surface coating. The crit. indentation load for the indentation-induced delamination of the coating from the substrate increases with the third power of the indentation depth and is a linear function of the reciprocal of the coating thickness. The indentation-induced delamination of SR399 ultrathin surface coatings over acrylic substrate was evaluated, using the nanoindentation technique for coating thicknesses of 47, 125, 220 and 3000 nm. For the submicron coatings, the dependence of the crit. indentation load on the coating thickness supports the elastic model. The interfacial strength is found to be 46.9 MPa. In contrast, the polymeric coating of 3000 nm displays multiple "excursions" in the loading curve, and the crit. indentation load is a linear function of the indentation depth.

Geng, K.; Yang, F.; Grulke, E. A., Nanoindentation of submicron polymeric coating systems. *Materials Science & Engineering, A: Structural Materials: Properties, Microstructure and Processing* **2008,** *A479* (1-2), 157-163.

Abstract. Characterization of the mech. properties of layered structures is of importance for the applications of nanoscale multilayer materials. Nanoindentation experiments of bilayer structures have been performed with polymeric coatings of 47, 125, 220 and 3000 nm on acrylic substrates of 3 mm. The coatings have higher elastic modulus and flow resistance than the substrates. The reduced relaxed contact modulus decreases with the increase in the indentation load for all the coating systems. A semi-empirical relation is developed to correlate the ratio of the coating modulus to the substrate modulus with the depth of elastic recovery. Using this relationship, the elastic modulus of the polymeric coatings is found to be 4.5 GPa. The flow behavior of the coating systems subjected to a const. indentation load is shear thinning and can be described by a linear relation between the creep depth and the square root of the indentation load with a stress exponent of 1/2 at small indentation loads for the 3000 nm coating system and at large indentation loads for the 47, 125 and 220 nm coating systems.

Druffel, T.; Buazza, O.; Lattis, M.; Farmer, S.; Spencer, M.; Mandzy, N.; Grulke, E. A., The role of nanoparticles in visible transparent nanocomposites. *Proceedings of SPIE* **2008,** *7030* (Nanophotonic Materials V), 70300F/1-70300F/9.

Abstract. Metal oxide nanoparticles can be used in thin film polymer systems to engineer specific material properties while maintaining visible transparency. High loadings of nanoparticles in a polymer can manipulate refractive index, modulus, and UV absorption over a wide range. Because the polymer binders can be allowed to dominate the phys. properties, these systems are ideal where materials undergo large strains. While stable dispersions of sub-100nm diam. $CeO_2$, ZnO, and $SiO_2$ are well understood and com. available, our group also developed a stable dispersion of $TiO_2$ nanoparticles. These metal oxides are significantly harder than the host polymer, have high UV absorption, and cover a large refractive index range. Our group has successfully incorporated these materials into PMMA thin films with loadings up to 60% by vol. (approaching the theor. close packing of spheres). These thin film nanocomposites have been successfully incorporated into 30 layer, sharp cut optical filters that easily withstand large strains induced by mech. loading and thermal cycling. In these films we have adhered to the rule that nanoparticle diam. should be one-tenth the wavelength of visible light. As the thickness of the overall filter stack increases, light scattering is intensified, so the dimensions and refractive indexes of the nanoparticles become crit. for highly transparent systems. We study here the interactions of particle dimensions, refractive index, loading, thickness, and transparency in nanocomposites.

Task 3. Broadband reflective self-assembled coatings.
The team wrote a paper [26] and presented a poster [27] on the thin film mirror in IR**.**
Druffel, T.; Mandzy, N.; Sunkara, M.; Grulke, E., Polymer nanocomposite thin film mirror for the infrared region. *Small* **2008,** *4* (4), 459-461.

Transparent thin films consisting of a UV cured polymer with metal oxide nanoparticles were spin coated onto a polycarbonate substrate to build a polymer nanocomposite IR mirror. The resulting coating was analyzed using an IR spectrophotometer and TEM. The stack showed good interfacial adhesion and performed as predicted by theoretical models.

Druffel, T., Mandzy, N., Sunkara, M., Grulke, Polymer nanocomposite thin film mirror for the infrared region, poster, Gordon Conference – Composites, 13-18 January 2008, Ventura, CA.

Abstract. Thin film metal oxide coatings have been used for electromagnetic filters from the UV to the infrared regions for over half a century. Deposition of metal oxide layers onto a substrate has typically been accomplished using vapor deposition techniques[1] and more recently sol-gel methods[2]. These coatings provide very good optical and mechanical performance under abrasion, thermal cycles and variable humidities when applied to substrates with similar moduli and hardnesses. When conventional metal oxide coatings are applied to flexible, relatively soft substrates such as polymers, mismatches in mechanical properties can reduce interfacial adhesion or accelerate mechanical failures. This team developed anti-reflective optical filters utilizing self-assembled thin film polymer nanocomposites on polymer substrates. This poster shows a low-haze coating of fifteen discrete layers with a reflectance exceeding 90% near 1 mm wavelength.

### 4.3.3 Related Research Work

The team has collaborated on a number of SBIR awards from the National Science Foundation and the Department of Energy (Phase I). One from NSF has completed Phase II, and the product has been commercialized.

## 5. Conclusions

Nanocomposites based on crystalline metal oxide nanoparticles with controlled particle size distributions and crosslinkable polymers as the continuous phase can be used to develop coating systems with a range of optical properties. These material systems fit into conventional manufacturing systems, and complex optical designs can be constructed to specification. By using conventional optical filter design tools, it is possible to make the coatings anti-reflective, reflective at specific wavelengths, and colored (i.e., ‘manufactured color’). Functionalization of the nanoparticle surface is important for creating uniform dispersions in the continuous phase. The average particle size, the particle size distribution and agglomeration all affect the haze and transparency of the system. The nanocomposite coatings can have excellent adhesion to polymeric substrates, and therefore, low strain at the interface over a range of temperatures and imposed strains.

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## List of Acronyms, Abbreviations and Symbols

| ACRONYM | DESCRIPTION |
|---|---|
| **AR** | **Anti-reflective** |
| **ODC** | **Optical Dynamics Corporation** |
| **PMMA** | **Poly(methyl methacrylate)** |
| **PVD** | **Physical vapor deposition** |
| **SEM** | **Scanning electron microscope** |
| **TEM** | **Transmission electron microscope** |
| **UKRF** | **University of Kentucky Research Foundation** |
| **UV; UV-Vis** | **Ultraviolet; Ultraviolet-visible** |
| **μm** | **micrometer** |